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Experimental testing of cooling internal loads with a radiant wall

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Abstract

Thermally activated building systems (TABS) consist of pipes or ducts embedded in the building structure. This is a well-known technology for its capability to reduce energy use for cooling buildings. Additionally, TABS help integrating renewable energies, such as free-cooling with ground heat exchangers (GHE). However, TABS cooling load is sensitive to the internal load, and the use of GHE for free-cooling is limited to low energy buildings. In a previously published research, a radiant wall cubicle without internal gains demonstrated to achieve significant energy savings. However, the current research showed that under domestic and office scheduled internal gains equivalent to 42 $W \cdot m^{-2}$ the radiant cubicle increased its energy consumption for cooling more than the reference cubicle with air-to-air heat pumps. As a result, the radiant cubicle used around 20% more energy than the reference at air temperature set-point 24 ºC but saved around 20% compared to the reference at 26 ºC. Despite this, the radiant wall could still reduce the cooling cost through peak load shifting even though it showed to consume more energy than a conventional HP.

Keywords: Thermally Activated Building Systems (TABS); Radiant Walls; Radiant Cooling; Internal loads; Ground Heat Exchanger (GHE); Energy efficiency in buildings

Nomenclature

TABS	Thermally activated building systems
HP	Heap pump
AAHP	Air-to-air heat pump
GSHP	Ground source heat pump
GHE	Ground heat exchanger
EER	Energy efficiency ratio
COP	Coefficient of performance
DB	Dead band

1. Introduction

Thermally Activated Building Systems (TABS) have proven their great potential for increasing energy efficiency in buildings. This fact has encouraged much research in this field, as reflected in the most recent reviews regarding the key issues of TABS [1] and the main challenges in the control of this technology [2]. The potential of TABS is especially interesting when considering that the building sector in Europe accounts for about 40% of the energy use [3]. The huge contribution of buildings to energy use and greenhouse gas emission highlights the potentiality of this sector for targeting energy efficiency strategies and policies, as reflected in European Directive 2010/31/EU [3] and more recently in the Paris COP21 agreement [4]. Consequently, the current situation demands the implementation of energy efficient technologies that also help to increase the contribution of renewable energies, requirement that TABS can fulfil completely.

TABS consist of pipes or ducts embedded in the building structure, such as floors, ceilings, in-floor slabs or walls. These pipes or ducts exchange heat directly with the building thermal mass, heat that is later exchanged with indoor space through the building surfaces. First, this interaction with the thermal inertia is useful for storing heat, which can help buffering the indoor temperature fluctuations caused by internal gains or outdoor weather conditions. Second, TABS can use the big surfaces of the building to exchange heat with indoor spaces. This allows achieving significant heat flux even with low temperature gradients [5]. Consequently, TABS can be used for low temperature heating and high temperature cooling, which improves the efficiency of heating and cooling systems or allows for integration of renewable energy sources [6] such as free-cooling with cool night air [7] or ground heat exchangers (GHE) [8]. Finally, TABS mostly exchange heat by radiation with occupants. Consequently, better indoor comfort conditions can be achieved by properly regulating mean radiant temperature and, therefore, at adequate operative temperature range [9]. Furthermore, TABS characteristics imply advantages such as integration to the building design and, because of the absence of fans, quiet operation and low draught risk. However, TABS also have disadvantages such as higher investment cost than conventional HVAC systems, control complexity due to its high thermal mass, and acoustic insulation issues, as raised floors and suspended ceiling limit TABS heat exchange capacity [1].

TABS show good synergy with GHE, especially in free-cooling conditions, as shown in the research on this topic. A simulation study showed that TABS assisted with ventilation had higher cooling energy demand than a conventional variable air volume (VAV) cooling system [9]. However, regarding primary energy intensity VAV used 20 % more energy, as TABS provided cooling without any vapour compression cycle, just using a ground heat exchanger. A method for pre-sizing boreholes to apply geo-cooling was defined for office buildings [10]. The method highlighted the requirement of low energy buildings, using a building with TABS as case study. Furthermore, it took into account that the boreholes were used for free-cooling and to supply a ground source heat pump for heating. On the free-cooling side, a simulation study showed that GHE supplying to radiant floors could achieve COP around 25 [11]. Moreover, it pointed out that the GHE supplied a relatively high water temperature for cooling, which helped avoiding condensation on TABS surface. Similarly, a hybrid system with radiant floor supplied by GHE complemented by a GSHP showed that the energy efficiency ratio (EER) was about five times higher with free-cooling compared to the heat pump [12]. Furthermore, the free-cooling system caused less temperature variation in the soil.

Previous research carried out by the authors showed the high potential for energy savings of a radiant wall coupled to a geothermal system compared to a conventional envelope and an air-to-air heat pump (AAHP). In heating mode, the ground source heat pump (GSHP) achieved savings over 20% [13]. Similarly, in free-cooling mode the radiant wall cubicle coupled to a GHE achieved savings higher than 50% depending on the set-point [8]. However, some research has shown that in well insulated buildings, internal loads have higher impact in the cooling load than the outdoor conditions [14]. Additionally, other studies showed that TABS cooling load was sensitive to internal loads [15]. Furthermore, indoor comfort considerations or other issues related to superficial condensation limit the surface temperature of TABS, which results in a limited cooling capacity. For vertical TABS a maximum cooling capacity of 72 $W \cdot m^{-2}$ was suggested [16].

The current paper extends previous research on free-cooling analysis within a radiant cubicle with GHE [8]. As mentioned above, the radiant wall can have a higher cooling load than other HVAC systems. Furthermore, the GHE have limited cooling capacity related to their sizing, undisturbed ground temperature, and ground characteristics. Consequently, a scenario with high internal loads can significantly reduce the performance of the system. Therefore, the study focuses on the influence of internal gains on the cooling and peak load shifting capacity of a radiant wall cubicle coupled to a GHE.

2. Experimental set-up

The experimental set-up was installed in Puigverd de Lleida (Lleida, Spain) and consisted of three house-like cubicles. Each cubicle consists of an individual building of a single room with all envelope exposed to the outdoor, as shown in Figure 1. The internal size of the room is 5.25×2.7×2.7 m, of which the long sides faced North and South. Each cubicle has two doors in the North wall but no windows or other openings. Furthermore, the doors are airtight to minimize infiltration. With this set-up, the cubicles allow the comparative study of the envelopes under outdoor conditions, but with a controlled number of variables.

Figure 1. Radiant Wall cubicle and reference cubicle

2.1. Cubicles characteristics

The radiant cubicle was built with 285×185×195 mm alveolar bricks. The radiant loops were embedded in the indoor surfaces of the wall and were built with 16 mm diameter and 1.8 mm thickness polyethylene pipes embedded 36 mm deep in grooves spaced 150 mm. The flow and return of each loop was distributed in alternate grooves so that inlet and outlet were close, and then the temperature difference in the wall surface was minimized. The schematic distribution of pipes is reported in Figure 2. The pipes were divided into five loops of equivalent lengths (two on the South wall and one on the North, East and West walls, see Figure 2) connected to a common manifold supplied by an Ecogeo B2 heat pump [17] working in GHE mode (free-cooling). The GHE used two boreholes each with two U-pipes descending up to 20 m and 40 m, respectively. The wall had 60 mm of expanded polystyrene boards on the outer surface, protected from the outdoor by an open joint ventilated facade of 5 mm fibrocement boards and

60 mm of air channel. The system was controlled by the integrated controller of the geothermal heat pump, which allowed adjusting the set-point according a timetable as well as adjusting the dead-band.

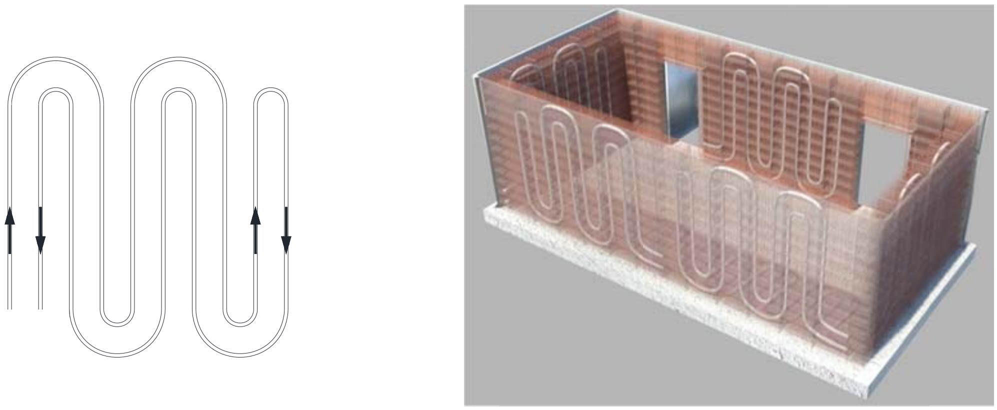

Figure 2. Schematic design of the loops (left) and positioning of the loops in the cubicle (right)

As comparison, two reference cubicles were built with alveolar bricks and equivalent wall thermal transmittance in steady-state (U-value of 0.5 $W \cdot m^{-2} \cdot K^{-1}$). Moreover, the roof and doors were built exactly as in the radiant cubicle, so that the only differences between the radiant cubicle and the references consisted of the ventilated facade and the cooling systems, as the references used commercial Fujitsu ASHA07LCC air-to-air heat pumps (AAHP) supplying fan coils. These heat pumps had a nominal power of 2.1 kW and a nominal cooling COP of 4.47. The AAHP were supplied with an integrated controller, which only allowed adjusting the set-point and the speed of the fan of the fan coil. This controller did not allowed scheduling different set-point along the day. The results of the second reference are only presented if the test conditions were different between cubicles.

More details of the experimental set-up can be found in previous articles [8,13].

2.2. Monitoring

The cubicles were monitored with of indoor air temperature and relative humidity, inner wall surface temperatures, water flow and energy consumption. Furthermore, the outdoor conditions were registered in terms of air temperature, relative humidity, wind speed and main direction, and global solar radiation over the horizontal plane. The sensors used for monitoring presented the following characteristics:

- Internal surface temperature of walls, roof and floor (Pt-100 DIN B calibrated with a maximum error of ± 0.3 ºC).

- Borehole temperatures at 5, 10, 20, 30 and 40 m (Sheathed Pt-100 DIN B calibrated with a maximum error of ± 0.3 ºC).
- Indoor air temperature and relative humidity (ELEKTRONIK EE21 with an accuracy of ± 2 %) at 1 m height of the centre of the room.
- External air temperature and relative humidity (ELEKTRONIK EE21 with an accuracy of ± 2 %).
- Global solar irradiance (Middleton Solar pyranometer SK08 ± 2 $W \cdot m^{-2}$).
- Electric energy consumption (Circutor MK-30-LCD-RS485 with an accuracy of ± 1 %).
- Pulse flow meters (Zenner MTKD-N with 1 pulse per litre and maximum operative temperature of 50ºC).
- Wind speed (DNA 024 anemometer).

3. Methodology

The main objective of this paper is to evaluate the performance of a radiant wall coupled to a GHE under intense internal loads in comparison to a conventional system. An infrared radiator HJM mod.301 was used to simulate heat load occupancy profiles, these had three electric resistances of 300 W each which could be activated separately, an thus each radiator could provide 300 W, 600 W, or 900 W.

3.1. <u>Tests</u>

The design parameters of the test consisted of set-point temperatures, active cooling schedule, internal gains and GHE dead-band (DB). This last parameter was intrinsic to GHE controller and it was used to deal with the thermal inertia of the system. DB avoided continuous on-off switching of the pumps when the indoor temperature was in close proximity to the set-point value. The DB introduced a range of set-back temperature around the set-point value, which implied switching on the pumps when the indoor temperature exceeded the top boundary switching them off when indoor temperature dropped down below the bottom boundary. In contrast, the AAHP works with a default DB that cannot be adjusted through the controller, although, by using the fan coil this system has fast response and does not need the DB for avoiding overcooling due to the dynamics of the system. Furthermore, some tests were carried out in different seasons to compare the influence of internal heat gains and outdoor heat gains. Therefore, tests were carried out in spring and in summer.

As commented above, the minimum power per radiator was 300 W. However, in order to ensure symmetry of the internal gains, two radiators facing opposite directions were used in each cubicle. Consequently, the minimum internal gains that could be applied in the experimental set-up was 600 W, which correspond to 42 W·m^{-2} per cubicle. This was the internal gains value used in all the tests, although different schedules of activation of the radiator were tested. The following tests were conducted:

- Maximum cooling capacity: These tests were carried out under continuous internal gains while cooling was allowed for 24 hrs operating at a set-point of 24 ºC. The AAHP worked under normal operation while the GHE was tested with a DB of 1 ºC and 1.5 ºC. The main objective was to obtain the maximum cooling capacity of the GHE and its performance both in spring and summer conditions. Additionally, the effect of the DB on the energy use of the GHE was checked.

- Scheduled internal loads: In these tests the internal loads followed occupancy schedules simulating the presence of activity (people and equipment). In the first case, an office schedule was applied with occupancy periods from 8:00 hrs to 13:00 hrs and from 14:00 hrs to 17:00 hrs. In the second case, a domestic schedule was applied with occupancy periods from 17:00 hrs to 8:00 hrs. Each schedule is consistent with occupancy profile reported in literature for office [18] and domestic [19] buildings, although, for the reasons mentioned above the internal gains were kept constant at 600 W. In both cases, the AAHP maintained a constant set-point for 24 hrs, with each reference maintaining 24 ºC and 26 ºC, respectively. In contrast, the radiant wall was operated with a night pre-cooling control strategy, with a set-point of 24 ºC from 0:00 to 8:00 and a set-point of 26 ºC for the rest of the day. The objective was to check the capability of the radiant wall to keep the comfort conditions under internal loads and using a control strategy that should mainly operate during low cost periods.

3.2. Measurements

The monitoring system registered the values of all sensors every five minutes. The thermal energy of the radiant walls and the boreholes were calculated assuming that the fluid temperature measured every five minutes could have been applied to the whole time interval as an average value. Moreover, the flow was calculated by dividing the amount of litres registered by the time step.

As a significant part of the heat exchange of the radiant wall was mainly by radiation, the indoor air temperature of the cubicle was not identified as a good indicator of thermal comfort conditions, since underestimation of radiant power was expected. Consequently, the more representative operative temperature was used to evaluate thermal comfort conditions. As this parameter could not be directly measured with the used experimental set-up, it was calculated using air temperature sensors and indoor surfaces temperature sensors. The calculation was done according to the procedure from ASHRAE [20] for moderate microclimate conditions. First the mean radiant temperature was calculated for a point at the centre of the cubicle at a height of 1 m, which was the actual position of the air temperature sensor. Then, the operative temperature was calculated with the average between mean radiant temperature and air temperature, as it was assumed that air speed was lower than 0.2 $m \cdot s^{-1}$.

3.3. Cost calculation

The operational cost of the AAHP and the GHE were calculated according to variable electricity tariff in Spain. Moreover, the fix cost of the electric connection was not considered because it is related to the power term and this parameter was not influenced by the research of this paper. The electricity cost corresponded to 0.065514 $€ \cdot kWh^{-1}$ in the low cost period, from 22:00 hrs to 12:00 hrs, and 0.145586 $€ \cdot kWh^{-1}$ the rest of the day [21].

4. Results and discussion

4.1. Maximum cooling capacity

Four experiments were conducted for the maximum cooling capacity assessment. The spring tests were done from May 16th to May 23rd 2016 for a DB of 1 ºC and from May 28th to June 6th 2016 for a DB of 1.5 ºC. Similarly, summer tests were carried out from July 26th to August 1st 2016 for a DB of 1 ºC and from August 2nd to August 10th 2016 for a DB of 1.5 ºC. Weather conditions during each test are summarized in Table 1 and Figure 3.

Table 1. Summary of test conditions for maximum cooling capacity test

	Average outdoor temperature (ºC)	Average minimum outdoor temperature (ºC)	Average maximum outdoor temperature (ºC)	Average accumulative daily radiation ($MJ \cdot m^{-2}$)	Accumulative daily radiation standard deviation
Spring DB 1ºC	18.1	9.8	26.7	8.24	1.14
Spring DB 1.5ºC	19.5	11.5	28.4	8.39	1.39
Summer DB 1ºC	26.6	16.2	36.7	8.24	0.35
Summer DB 1.5ºC	25.8	16.4	35.1	7.83	0.53

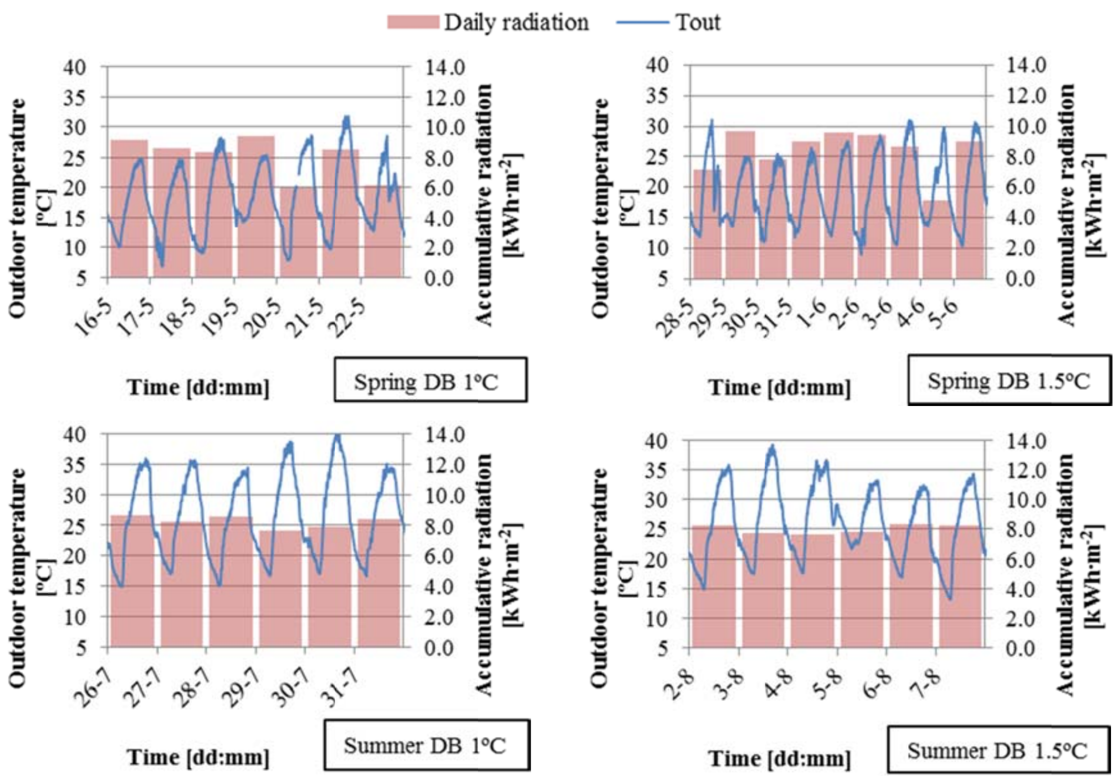

Figure 3. Outdoor temperature and daily accumulated solar radiation for maximum cooling capacity test

Under continuous internal gains the radiant wall coupled to GHE consumed more energy than AAHP in all the tested conditions. The electric power consumption of the system was constant at 250 W. This corresponded to the two circulation pumps, one for boreholes and the other for the radiant walls, both working at constant flow rate. However, the average thermal power varied depending on the length of activation. The longer the activation period the more the temperature of the boreholes increased, and thus the temperature gradient between the set-point and the boreholes decreased. Consequently, the thermal power of the system decreased along the activation periods. Figure 4 shows the borehole temperatures and the flow, inlet and outlet temperature of the GHE along the experiments.

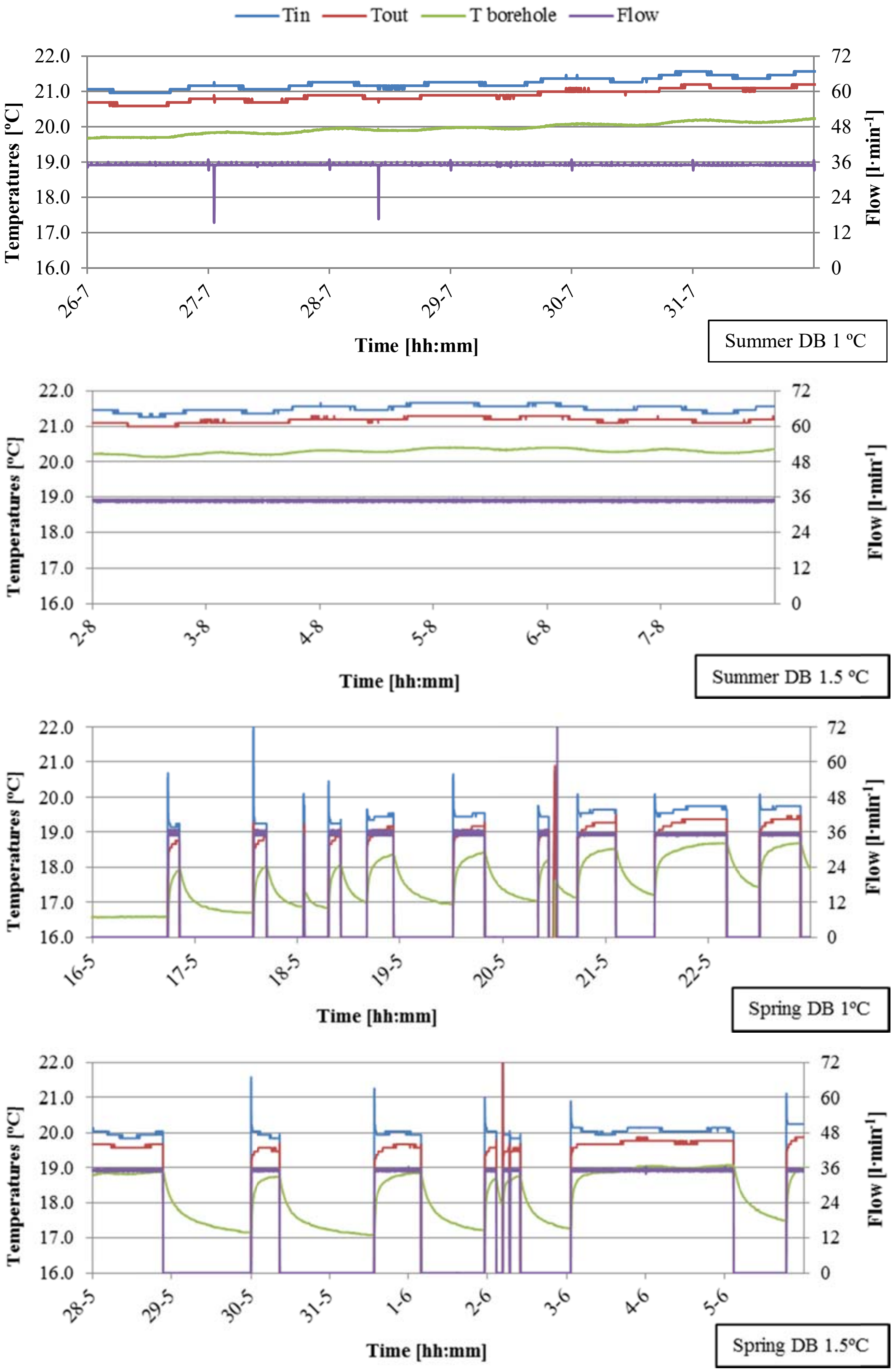

Figure 4. Borehole temperature, inlet and outlet temperatures and flow of the GHE during maximum cooling capacity tests (note inlet and outlet temperature are only relevant with flow)

In summer the GHE needed to operate for 24 hrs, as it had not enough power to cool down the cubicle in the range of the dead-band. Table 2 shows that the average thermal power decreased from the first summer test (DB 1 ºC) to the second one (DB 1.5 ºC). Both tests were executed consecutively, thus these results are consistent with the increase of the boreholes temperature during the test operation, as reflected in Figure 4. As the flow was constant, the thermal power decreased continuously as the temperature gradient decreased. On the other side, the heat loads in spring were low enough for the GHE to cool down the cubicle and work under the dead-band cycle. In these conditions, the temperature at the boreholes recovered its base values between activations, although some heat storage was observed in the boreholes. Consequently, the temperature gradient during activation was higher and this resulted in a higher thermal power and a better overall performance of the system, as shown in Table 2. Finally, the different tested DB did not show significant performance modification. However, the test conditions limited the influence of this parameter because the internal load was similar to the cooling capacity of the system, and thus the activation periods were very long in all cases or the system had to operate constantly.

Table 2. Results of maximum cooling capacity tests

Test	Energy use (kWh)			Operation time (% of daily hours)		Radiant wall average thermal power (W)	GHE COP	Heat exchanger efficiency
	Radiant wall+GHE	Reference	Savings	Radiant wall+GHE	Reference			
Spring 1ºC DB	14.697	9.262	-36.98 %	19.89 %	28.81 %	742.16	3.08	70.84%
Spring 1.5ºC DB	29.103	17.110	-41.21 %	52.70 %	86.81 %	643.34	2.66	70.02%
Summer 1ºC DB	37.380	22.944	-38.62 %	100 %	95.94 %	577.25	2.38	67.36%
Summer 1.5ºC DB	50.480	24.530	-51.41 %	99.92 %	85.44 %	493.22	2.06	68.39%

4.2. Scheduled internal loads

The office schedule internal loads test was carried out from July 7th to July 14th 2016 followed by the domestic schedule test which was carried out from July 16th to July 25th 2016. Weather conditions for both tests are summarized in Table 3 and Figure 5.

Table 3. Summary of test conditions for maximum cooling capacity test

Schedule	Average outdoor temperature (ºC)	Average minimum outdoor temperature (ºC)	Average maximum outdoor temperature (ºC)	Average accumulative daily radiation (MJ·m^{-2})	Accumulative daily radiation standard deviation
Office	26.2	17.4	35.1	8.57	0.70
Domestic	25.2	14.4	36.0	8.27	1.14

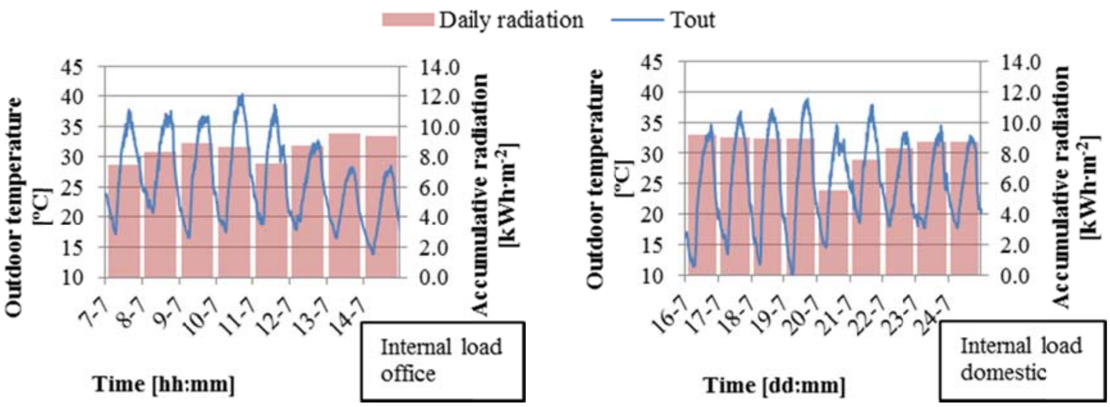

Figure 5. Outdoor temperature and daily accumulated radiation for scheduled internal loads

The results show that the radiant wall coupled to a GHE was able to shift the peak load to low cost periods under daily scheduled internal gains. The radiant wall kept indoor temperature close to the comfort range for most of the occupancy period, while it was mostly activated during low cost periods thanks to the pre-cooling strategy. This led to higher cost savings than energy savings, as summarized in Table 4. Especially relevant was the comparison with the reference at set-point of 24 ºC, against which the radiant cubicle presented energy savings despite having higher energy use. Additionally, the pre-cooling control strategy resulted in a clear ON-OFF pattern of the GHE. As a result, the GHE was active during the night, but during the day it did not work, which allowed the regeneration of the borehole temperatures, as shown in Figure 6.

Table 4. Results of scheduled internal loads tests

	Reference		Radiant		
	Set-point	Energy (kWh)	Energy (kWh)	Energy savings (%)	Economic savings (%)
Office internal gains	26ºC	13.499	16.570	-18.53%	29.70%
	24ºC	20.182		21.80%	51.74%
Domestic internal gains	26ºC	14.079	18.450	-23.69%	22.83%
	24ºC	20.787		12.67%	47.81%

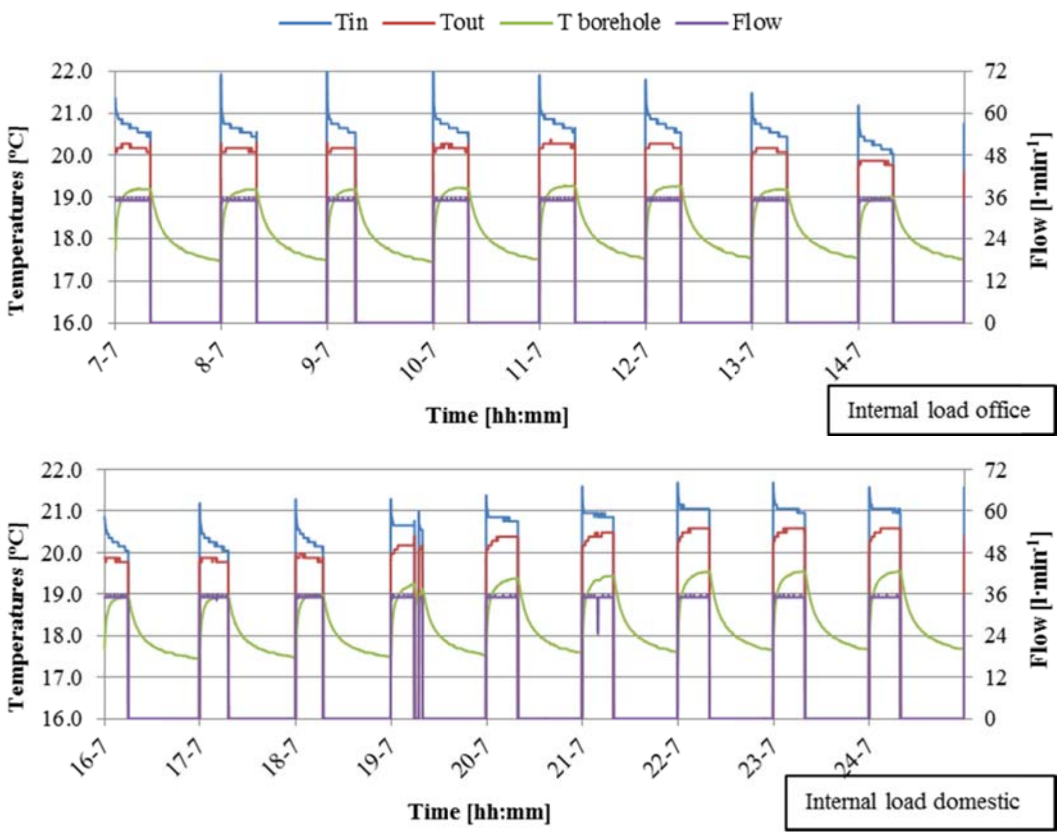

Figure 6. Borehole temperature, inlet and outlet temperatures and flow of the GHE during maximum cooling capacity tests (note inlet and outlet temperature are only relevant with flow)

In the conditions of domestic schedule, the radiant wall carried out the pre-cooling during the occupancy, as shown in Figure 7. Despite the internal gains, the GHE was capable to cool down the cubicle, even though it did not manage to go down to the pre-cooling set-point. Nevertheless, the pre-cooling operation was unsuited for domestic scheduled internal gains, as there was a mismatch between the active period of the system and the occupancy timing. This implied that the GHE started the intensive cooling after several hours of occupancy and after a whole day under hot weather conditions, which had caused the cubicle to warm up significantly. Furthermore, the end of GHE operation and the lowest temperature in the cubicle happened at the end of the occupancy period, when comfort conditions were not required anymore by potential occupants.

Noticeably, the AAHP of the reference cubicles had an energy use profile that followed the internal and solar gains. The energy consumption was at its minimum early in the morning and it progressively increased along the day, matching the solar gains. At 17:00 hrs there was a peak on energy use, when solar gains were high and internal gains started. However, during the night, the energy use of reference cubicles progressively decreased, indicating that heat loses to outdoor ambient helped to reduce the cooling load caused by internal gains. Furthermore, the lower outdoor temperature also improved the COP of the AAHP. In contrast, the GHE had constant and high energy use during the pre-cooling period, while it did not consume any energy during the rest of the day.

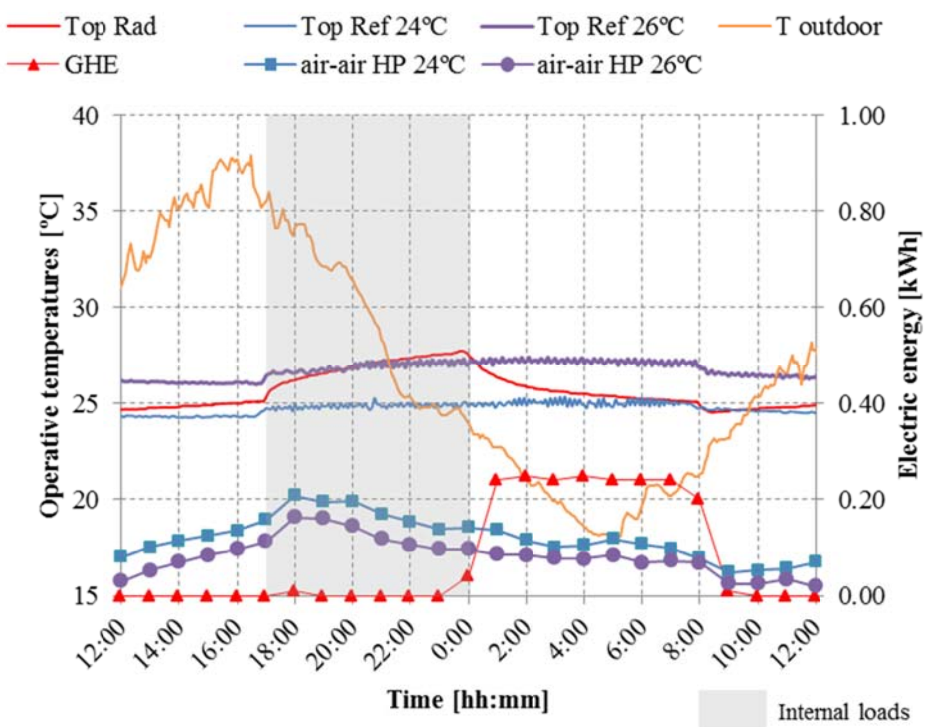

Figure 7. Operative temperatures and hourly energy use for domestic internal load test (July 21st to July 22nd)

The pre-cooling strategy better suited the office internal gains. As shown in Figure 8, at the end of the pre-cooling, the temperatures of the cubicle are at its lowest points. Then, the internal gains are buffered during the day, limiting the high temperatures to the afternoon. Moreover, as in the previous test, the GHE coupled to the radiant wall consumed constant power during active periods. This contrasts with the references, whose energy use followed the internal and solar gains. Two peaks of energy use were observed, in correspondence to the two occupancy periods. Furthermore, there was a progressive increase of the energy use during the day, reflecting the solar gains and reduced efficiency of AAHP because of increasing outdoor temperature. Noticeably, the cooling load rapidly decreased, immediately after the internal load stopped at the afternoon, indicating that the heat pumps could easily remove the heat accumulated in the indoor air. After that, the cooling load stabilized before progressively decreasing during the night, implying that the heat pumps were slowly removing the heat stored in the cubicle thermal mass. In this phase, the heat loses to outdoor ambient helped to reduce the cooling load.

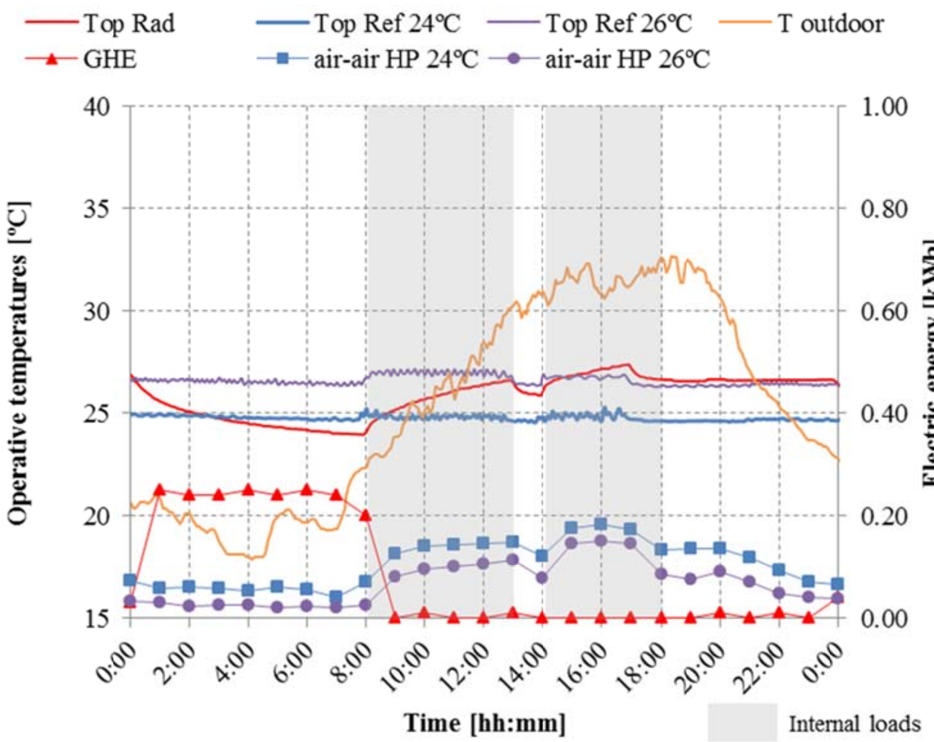

Figure 8. Operative temperatures and hourly energy use for office internal load test (July 12th)

5. Discussion

The test site had an undisturbed ground temperature of 17 ºC, which together with a high water table presented a good potential for free-cooling, as it was proved in previous research [8]. However, the tests with internal loads showed the limited cooling capacity of the GHE, which resulted in a poor performance of the system in terms of energy use. In the tested conditions, the average thermal power removed from the walls was between 742.16 W and 493.22 W, which correspond to a cooling capacity of the radiant walls of 20.36 $W \cdot m^{-2}$ and 17.65 $W \cdot m^{-2}$. These values were much lower than the theoretical maximum of 72 $W \cdot m^{-2}$ [16] because of the limited supply temperature achieved by the GHE. This is relevant point to take into account in an actual implementation of this system, correct sizing of the boreholes and the heat exchanger would be critical to ensure that the system could deal with the heat loads. However, as the radiant wall only deals with sensible loads, in an actual application the system should be complemented by a ventilation system, specifically designed to help fulfilling all the cooling loads.

Additionally, the experimentation clearly showed that the radiant wall works better under intermittent operation. Due to low conductivity of boreholes, the temperature rose during the operation, causing a decrease of thermal power during continuous operation. A control strategy that considers this factor could achieve better average thermal power and optimize the overall performance of the system, as the total operation time could be reduced [22]. This intermittent operation would also help dealing with the thermal lag of the radiant wall.

A good strategy for exploiting the potential of the radiant wall coupled with the GHE was the night pre-cooling. This operation mode ensured certain intermittency of the system by storing energy in the wall during a period. Then, the thermal inertia of the system buffered the heat gains during the rest of the day while the temperatures in the boreholes regenerated. This was useful for shifting the energy use to low cost periods, which resulted in cost savings despite the increased energy use in certain cases.

Additionally, the internal gains used in the tests were very high. According to ASHRAE [20], considering a load factor of a heavy density office occupied by two people on moderately active office work, the sensible heat gains would be around 39 $W \cdot m^{-2}$, which is lower than the 42 $W \cdot m^{-2}$ used in the experimentation. This meant that the test conditions were carried out under very heat intensive conditions, an upper boundary of office heat loads. Regarding this, the research on the reduction of energy use in buildings is focused on improving the performance of the systems as well as on the reduction of the heating and cooling loads. Consequently, the tested conditions were representative of a current building, but do not match with a future scenario of low energy buildings. This scenario will synergistically improve the performance of the radiant wall coupled to a GHE.

Finally, the radiant walls were built as normal brickwork wall in which grooves were cut, the pipes embedded and concreted. As a result, the radiant walls were much more expensive than the conventional ones. The initial work was the same, however, cutting the grooves added many person-hour and a lot of waste. Then, the pipes had to be embedded and concreted, which was a complex and time consuming task. The cost of all this tasks made this radiant wall design unfeasible for implementation in buildings in the current prototype configuration. Nevertheless, this was the simplest tailored approach found for testing a radiant wall, as there were no commercial systems for it. This said, the currently available results encourage further research in order to bring the radiant wall to commercial stage.

The radiant wall showed promising capabilities toward achieving zero-energy buildings. First, it could reduce the energy demand of the building. Moreover, it allowed for integration of renewable energies such as free-cooling with GHE. However, the main asset was the thermal energy storage capacity, which could be the key point for integration of renewable energies in the building. The active use of the thermal inertia could allow exploiting intermittent energy sources such as free-cooling with cool night air [7] or off-setting the energy use of a heat pump by activating it while PV panels produce energy during the day [23].

6. Conclusions

The influence of internal loads on the performance of a radiant wall coupled to a GHE was experimentally studied. The main objective of the research was to show the capacity of the system to keep thermal comfort under different weather conditions and internal loads schedules, evaluating both its cooling capacity and peak load shifting ability.

The GHE limited the cooling power of the system, as the thermal power was proportional to the temperature gradient between the boreholes and the indoor temperature. As the temperature in the boreholes tended to increase during activations, the thermal power tended to decrease in long activations. Despite this, the radiant wall coupled to the GHE could maintain comfort conditions during its activation periods. Moreover, the tested conditions corresponded to a high energy intensive office. In case of less energy intensive building, for example residential buildings, the system would better exploit the potentiality of free-cooling.

Furthermore, the average thermal power and overall efficiency of the radiant wall coupled to GHE could be improved by intermittent operation. The low conductivity in the boreholes and inside the walls resulted in the progressive increase of the temperatures in the boreholes while the temperatures in the wall decreased during operation, this resulted in a reduction of temperature gradient. Consequently, continuous cooling resulted in a progressive decrease of the cooling capacity and the overall system efficiency. However, with intermittent operation the temperatures at the boreholes could be regenerated, thus improving the heat transfer efficiency.

Additionally, the radiant wall showed its capability to store energy and shift the peak load, even under very hot weather conditions and intense internal gains. With a good management of the comfort range the system could shift most of its active time to low energy cost periods or to periods with renewable energy availability, such as consuming the power directly supplied by PV systems. As a result of this potentiality, the tests under scheduled internal gains showed that in some cases the radiant wall coupled to a GHE consumed more energy than the references, despite this, the pre-cooling strategy resulted in a lower operational cost of the radiant cubicle in all cases.

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